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16. ABSTRACT

Previous work indicated dose-rate thresholds in the effects of UV-B on the near-surface larvae of three shrimp species. Additional observations suggest that the total dose response varies with dose-rate. Below 0.002 Wm^{-2} [DNA] irradiance no significant effect is noted in activity, development or survival. Beyond that dose-rate threshold, shrimp larvae are significantly affected if the total dose exceeds about 85 Jm^{-2} [DNA]. Predictions cannot be made without both the dose-rate and the dose.

These dose/dose-rate thresholds are compared to four-year mean dose/dose-rate solar UV-B irradiances at the experimental site, measured at the surface and calculated for 1 m depth. The probability that the shrimp larvae would receive lethal irradiance is low for the first half of the season of surface occurrence, even with a 44% increase in damaging UV radiation.

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Dose/Dose-Rate Responses of Shrimp Larvae to UV-B Radiation *

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Summary. Previous work indicated dose-rate thresholds in the effects of UV-B on the near-surface larvae of three shrimp species. Additional observations suggest that the *total dose* response varies with dose-rate. Below 0.002 $Wm^{-2}_{[DNA]}$ irradiance no significant effect is noted in activity, development, or survival. Beyond that dose-rate threshold, shrimp larvae are significantly affected if the total dose exceeds about 85 $Jm^{-2}_{[DNA]}$. Predictions cannot be made without *both* the dose-rate and the dose.

These dose/dose-rate thresholds are compared to four-year mean dose/dose-rate solar UV-B irradiances at the experimental site, measured at the surface and calculated for 1 m depth. The probability that the shrimp larvae would receive lethal irradiance is low for the first half of the season of surface occurrence, even with a 44% increase in damaging UV radiation.

Introduction

The potentially serious problem of stratospheric ozone depletion, through global atmospheric pollution, has recently been reviewed by the National Academy of Sciences (NAS 1979). The current estimate of eventual ozone decrease is 16.5%, with half of the decrease occurring in about 30 years. A 16.5% ozone loss would result in a 44% increase in damaging incident solar ultraviolet radiation (UV-B*), when the spectral energy of this additional UV is weighted according to the DNA action spectrum. It is not known how most organisms will respond spectrally to UV-B increases, yet the choice of weighting factors is important in predictions. In some organisms, for example, effects that parallel the erythemal action spectrum would lead to a predicted 37% increase in damaging UV for the same 16.5% decrease in stratospheric ozone (Allen and Gausman 1975). Other effects, corresponding to still other action spectra, may suggest negligible increases in damaging UV (NAS 1979; Smith et al. 1980).

Previous investigations of the effects of UV-B radiation on aquatic organisms have generally sought to determine biologically effective *dose-rates* and *total doses* (Worrest et al. 1978; Hunter et al. 1979; Karanas et al. 1979; Damkaer et al. 1980; Thomson et al. 1980). These parameters quantify factors associated with observed effects and are useful in comparing other experimental and natural conditions. Nevertheless, the independent application of either total dose or dose-rate in describing biological effects implies that there is reciprocity between dose-rate and duration, and that it is only the total dose that is important. Nachtwey (1975) and Damkaer et al. (1980) indicated that repair mechanisms in some aquatic organisms could keep pace with the damaging effects of UV-B radiation when that damage is produced slowly enough. That is, there is some dose-rate threshold below which detrimental effects are not observed, regardless of the total dose. This should be expected since many of these organisms are naturally exposed to significant UV-B radiation.

The specific objectives of this study were 1) to examine relationships between total UV-B dose and dose-rates in biological effects of UV-B radiation on shrimp larvae, and 2) to assess potential dangers to shrimp populations under increased solar incident UV-B radiation.

Materials and Methods

The results of our earlier investigation of the effects of UV radiation on shrimp larvae have been incorporated into the present study (Damkaer et al. 1980). These data represent the effects of UV irradiation on larvae of *Pandalus danae*, *P. hypsinotus*, and *P. platyceros* at Manchester, Washington. Except for the addition of controls using a clear Mylar® plastic sheet (0.25 mm thickness) as an optical filter for the cool-white and FS-40 sunlamp combinations, all new experiments were conducted as described in the previous work. The additional control organisms were exposed only to UV-A and visible light, since Mylar removes wavelengths below 315 nm (Fig. 1). As before, cellulose triacetate (CTA) filters over the lamp combinations admitted UV-B as well as UV-A to the test organisms.

In the earlier report, biologically effective UV-B irradiance was evaluated using the erythema (sunburning) action spectrum of Green et al. (1974). We still believe that the erythema action spectrum is a useful and appropriate weighting function for describing general effects and for comparing experimental irradiance levels. However, most investigators working with aquatic organisms have used the DNA action spectrum (Setlow 1974). To improve the comparability of our data, DNA-weighted effective doses have been calculated and both weighting systems have been included in a summary table. According to Green and Miller (1975), the relative energy effectiveness for DNA damage at each nm wavelength can be calculated:

$$\varepsilon_\lambda = \exp\left\{k\left[\frac{1}{1+\exp[(\lambda-\lambda_0)/\lambda_f]}-1\right]\right\}$$

where $k = 13.82$, $\lambda_0 = 310$, and $\lambda_f = 9$.

As with other weighting functions, the total DNA-damage effectiveness is then calculated by multiplying the observed values of absolute irradiance in each narrow wavelength region by the corresponding relative effectiveness (ε_λ) and summing these values for the wavelength band of interest.

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* UV-B = radiation in the middle ultraviolet wavelength range, 280–315 nm

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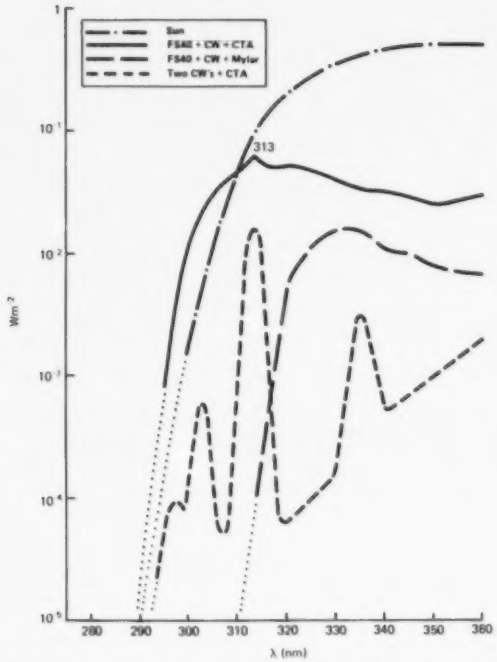

Fig. 1. Spectral irradiance of solar and artificial light sources, 280–360 nm, measured spectroradiometrically

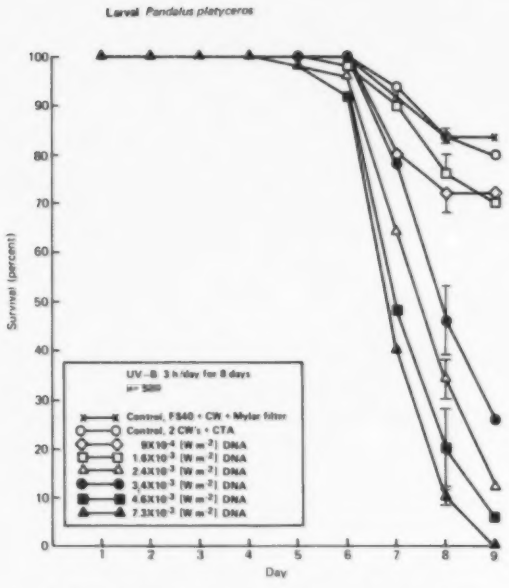
Larval Pandalus platyceros
Survival (percent)
Day
UV-B: 3 h/day for 8 days
Control, FS40 + CW + Mylar filter
Control, 2 CW's + CTA
9X10⁻⁴ [W m⁻²] DNA
1.6X10⁻³ [W m⁻²] DNA
2.4X10⁻³ [W m⁻²] DNA
3.4X10⁻³ [W m⁻²] DNA
4.6X10⁻³ [W m⁻²] DNA
7.3X10⁻³ [W m⁻²] DNA

Fig. 2. Percent survival from birth through 9 days of larval *Pandalus platyceros*, at eight levels of UV-B radiation. Temperature 8.3–8.6° C. Capped vertical lines represent 95% confidence limits of five replicates

Some of the uncertainties associated with the penetration of UV-B into various marine waters have been eliminated, but it has not yet been possible to make subsurface measurements at Manchester. In this study the penetration of UV-B was calculated using the attenuation coefficients of Smith and Baker (1979) for water type 4 (moderately productive waters with a high concentration of dissolved organic matter).

Results

The results of new experiments with the additional control group of organisms exposed to Mylar-filtered irradiance substantiated our earlier conclusions (Damkaer et al. 1980). That is, the major biological effects are from UV-B irradiation and not from UV-A. There were no significant differences ($\alpha = 0.05$) in activity or survival between larvae exposed to CTA-filtered cool-white control lamps and larvae exposed to Mylar-filtered cool-white and sunlamp combinations (Fig. 2). Statistically significant effects occurred above dose-rate thresholds similar to thresholds previously reported (Table 1). The new erythema-weighted threshold values of Table 1 are slightly higher due to regression refinements and the inclusion of wavelengths 285–289 nm.

For each treatment, at a particular dose-rate, a total dose was determined at either the time of first significant mortalities, or, where there were no significant mortalities, at the end of the experiment. The relationship between total doses and dose-rates at these times is shown in Fig. 3. The open circles represent the *maximum* combinations of dose-rate and total dose at which there was essentially complete survival. At these low dose-rates, the larvae can complete their near-surface development before high total doses are reached, so that doses above about 350 $Jm^{-2}_{[DNA]}$ are academic. The closed circles represent the *minimum* combinations of dose-rate and total dose at which

Table 1. Estimated biologically effective UV (285–315 nm) thresholds for principal experimental zooplankton groups

	Dose-Rate Wm^{-2}			Effective Daily Dose Jm^{-2}		Approximate days (Treatments) for Significant Effect on Activity or Mortality	Total Dose Jm^{-2}	
	Un-weighted	DNA Weighted	Erythema Weighted	DNA Weighted	Erythema Weighted		DNA Weighted	Erythema Weighted
Shrimp and Euphausid Larvae	0.44	0.0020	0.054	22	583	4	85	2,330
Crab Larvae (zoea)	0.63	0.0033	0.078	36	842	6	215	5,050
Crab Larvae (megalops)	1.06	0.0093	0.132	100	1,425	20	2,000	28,500
Euphausids (adults)	0.63	0.0033	0.078	36	842	6	215	5,050

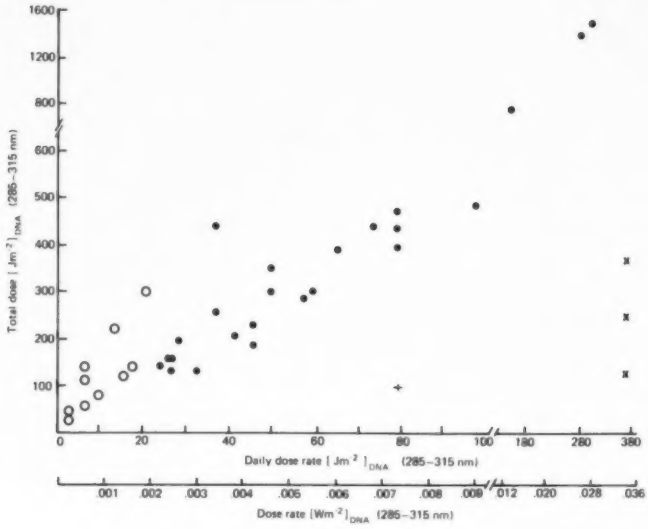

Fig. 3. Effects on shrimp larvae for various combinations of UV-B dose-rate and total dose. Open circles indicate maximum observed combinations for survival; other symbols indicate minimum observed combinations for mortality. See text for further explanation

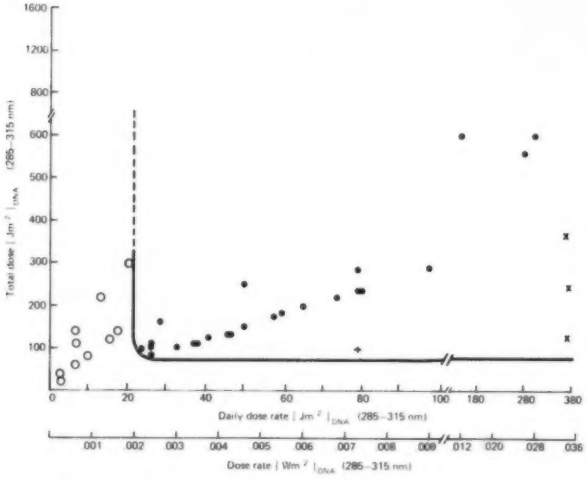

Fig. 4. Activity as an index of lethal effects on shrimp larvae for various combinations of UV-B dose-rate and total dose. Open circles indicate maximum observed combinations for normal activity and survival; other symbols indicate minimum observed combinations for inactivity. See text for further explanation

there was significant mortality. Combinations of greater dose-rate and dose are redundant, so that only experiments representing minimum points are indicated.

The upward dose/dose-rate slope suggested by the portrayal of simple survival data (Fig. 3) is an artifact of 1) the typical 3-hour per day exposure time, and 2) the several-day delay before death. This was substantiated by three separate treatments where shrimp larvae were irradiated at a high dose-rate for only 1, 2, and 3 hours, respectively (X's on Fig. 3). The irradiated larvae died after about 4 days, indicating that exposures beyond the first day would have been superfluous at that high dose-rate. In a second experiment (+on Fig. 3), larvae irradiated at a lower dose-rate for 3 hours on one day only also were dead by the fourth day. These experiments indicate that the lethal doses shown in Fig. 3 are much higher than minimal. Further, it is difficult to imagine how lower dose-rates could lead to lower lethal doses. For these reasons, it is believed that a line delineating a lethal dose/dose-rate zone would not slope upwards.

It had been noticed (Damkaer et al. 1980) that general activity of the irradiated organisms could also be used as a survival index, with the effect appearing one or two days earlier than mortality. Inactive shrimp larvae have not been seen to recover. Therefore, if significant decreases in activity are recorded, rather than survival, the artifacts of superfluous doses and delayed responses are in part eliminated (Fig. 4). However, for the reasons mentioned above, the line delineating the lethal dose/dose-rate zone at the higher dose-rates is believed to be horizontal. We have not yet experimented with dose/dose-rate combinations in the presumed safe zone directly below the horizontal line.

These observations indicate that there is a threshold for *both* the dose-rate and the total dose of UV-B. At low dose-rates, below about 0.002 $Wm^{-2}_{[DNA]}$, shrimp larvae can apparently tolerate and repair UV damage, even for the entire two to three weeks of near-surface occurrence. Beyond that dose-rate threshold, the shrimp larvae die if the total dose exceeds about 85 $Jm^{-2}_{[DNA]}$ (Fig. 4 and Table 1). Given any laboratory combination of UV-B dose-rate *and* total dose, predictions can be made regarding significant biological effects on these shrimp larvae.

Discussion

For several groups of near-surface zooplankton, including the larvae of the three shrimp species, we have superimposed the experimental daily dose thresholds on the four-year mean of the median surface UV-irradiances measured at the study site near Manchester, Washington (Fig. 5). At present ozone thicknesses, these thresholds are above the median solar incident UV-B levels except toward the end of the seasons of surface occurrence. With a 16% ozone reduction (NAS 1979), equivalent incident UV-B levels would be reached about three weeks earlier.

In assessing potential dangers to shrimp populations from increasing solar UV-B irradiation, the subsurface irradiance levels must be considered. The data from Fig. 4 have been replotted ignoring the unrealistically high dose-rates, so that the critical area between the safe and lethal dose/dose-rate zones can be examined (Fig. 6). The mean of the observed daily UV-B surface doses (present ozone thickness) between mid-February and mid-

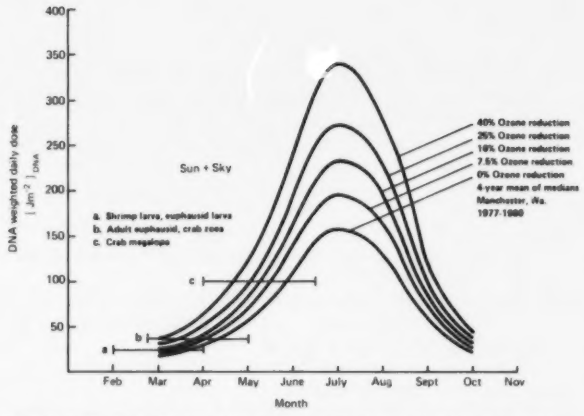

Fig. 5. Estimated effective UV-B solar daily dose at various atmospheric ozone concentrations, based on 4-year mean of medians; Manchester, Washington, 1977–1980. Dose increments are from the DNA-effective-dose/ozone-concentration relationship of NAS (1979). Also shown are approximate thresholds of UV-B daily dose for principal experimental zooplankton groups, in natural seasonal position

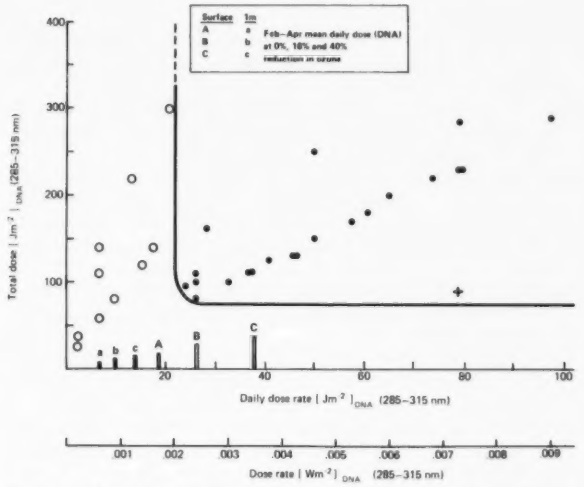
Surface 1m
A a Feb–Apr mean daily dose (DNA)
B b at 0%, 16% and 40%
C c reduction in ozone
Total dose [Jm⁻²]DNA (285–315 nm)
Daily dose rate [Jm⁻²]DNA (285–315 nm)
Dose rate [Wm⁻²]DNA (285–315 nm)

Fig. 6. UV-B dose/dose-rate safe and lethal zones (data from Fig. 4). Open vertical bars indicate mean February–April surface solar UV-B daily dose-rates at various atmospheric ozone concentrations; closed vertical bars indicate mean daily dose-rates at 1 m

April is within the experimentally determined safe zone. Daily doses calculated for 1 m depth are therefore even farther within the safe zone, so that presumably the shrimp larvae could tolerate these mean dose-rates for as long as they remained near the surface. With projected 16% or 40% ozone reductions, the total dose thresholds would be exceeded at the surface only if the mean dose-rates are attained for two or three consecutive days, but even then the calculated mean UV-B levels at 1 m would remain in the safe zone.

The actual vertical distributions of the shrimp larvae are not known, but in the laboratory stage I–III larvae are attracted to light and definitely prefer the near-surface. The larvae have not been seen to avoid even high UV-B irradiance (Damkaer and Dey, in press); probably they cannot sense this radiation in sufficient time to prevent burning. We are assuming that the younger shrimp larvae are constantly moving toward the

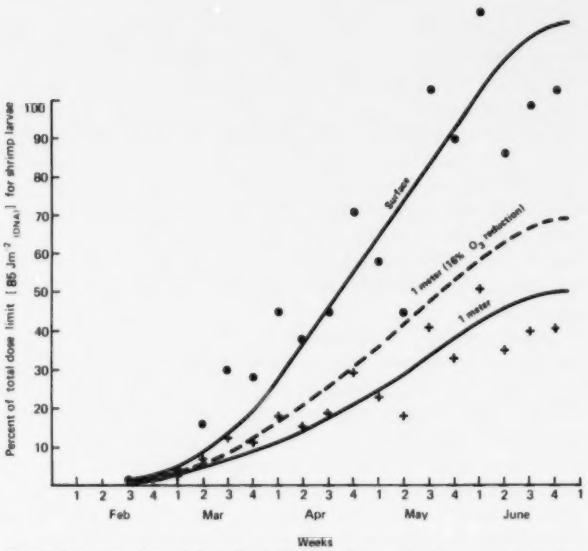

Fig. 7. Percent of total dose limit likely to be reached on any particular day; lethal doses accumulate only after dose-rate threshold is exceeded. Closed circles are 4-year weekly means of surface daily UV-B doses; +'s are these doses calculated at 1 m

surface, and that during the day the majority of the population is in the upper meter.

To determine the probability that particular shrimp larvae would receive lethal exposures of UV-B is a complicated problem, but an approximation is suggested by Fig. 7. This probability is obviously time-dependent, and even at the surface shrimp larvae are unlikely to encounter lethal daily or bi-daily UV-B exposures until the end of the surface season (mid-April). This is also about the time that the mean noon *dose-rate* exceeds the dose-rate threshold of 0.002 $Wm^{-2}_{(DNA)}$. Before then, a shrimp larva exposed daily to a one-third total dose limit for three consecutive days, for example, remains in the safe exposure zone because the dose-rate would be low (Fig. 6). At 1 m, the mean dose-rates in mid-April are still less than the shrimp's threshold dose-rates, yet the surface probabilities for lethal exposure may be sufficiently high at that time to limit the seasonal occurrence of the larvae. With a 16% ozone reduction, the present mid-April UV-B conditions would be reached near the end of March. If UV-B is a contributing factor in regulating the seasonal occurrence of shrimp larvae, ozone reductions may act to shorten the surface time available to the larvae. The seasonal relationships in the UV-B tolerance of different zooplankton groups (Fig. 5) suggest that UV irradiation is an important environmental factor. This has also been postulated by Hunter et al. (in press) for the surface occurrence of eggs and larvae of a number of clupeoid fishes.

Data on population dynamics and recruitment of shrimp stocks are insufficient to estimate the impacts of shortened surface seasons. It is possible that the greatest number of successful recruits are normally derived from early-season larvae and that increased UV-B would then have no appreciable direct effect on shrimp population stability. If late-season larvae are essential to maintain local populations, ozone reductions may lead to geographic range restrictions in these shrimp.

There have been few other studies on the effects of UV-B on zooplankton. Karanas et al. (1979) studied the responses of the developmental stages of the copepod *Acartia clausii*, the adult of which approaches the morphological grade and size

of the shrimp larvae of the present report. Unfortunately, the UV-B dose-rates used for stressing the copepods were very high, even though the daily doses were comparable to natural (Oregon coast) daily doses. If there were complete reciprocity this would not matter, but it is doubtful if reciprocity is the rule, particularly at the lower daily doses. Karanas et al. calculated the depths of daily doses found to have effects on *Acartia clausii* in the laboratory, and concluded that significant losses of these copepods could occur in the upper few meters. Since it is likely that the lethal dose depends on the dose-rate, the observed effects on these copepods should be investigated further using realistic dose-rates.

Hunter et al. (1979) studied the UV-B sensitivity of eggs and larvae of anchovy and mackerel. The anchovy were the more sensitive, and most attention was given to these. Even at the lowest experimental dose-rates, Hunter et al. indicated that the anchovy larvae were retarded in growth and development, and that it was unlikely any would be able to feed successfully. In subsequent studies (cited in NAS 1979), Hunter et al. lowered the dose-rates and found that the effect of total dose depended on the dose-rate and, therefore, reciprocity would not apply. Hunter et al. have not discussed a threshold effect, but the lowest experimental dose-rate at which they found significant morphological damage was 0.002 $Wm^{-2}{}_{[DNA]}$, which is identical to the dose-rate threshold found for the shrimp larvae of the present study. This may be the maximum dose-rate unprotected multicellular zooplankton can tolerate indefinitely.

Ultraviolet irradiation does adversely affect aquatic organisms. To what extent UV might do so in nature, to individual species, populations, and communities, cannot yet be predicted. But the potential effects are serious enough to warrant additional research. The most fruitful UV-related research areas would include the evaluation of UV action spectra (weighting factors) for zooplankton, UV effects on other important near-surface zooplankton groups, measurement of subsurface UV intensities, and the determination of probabilities that threshold UV dose-rates and doses would be exceeded at particular localities and times. It will also be necessary to determine the photorepair abilities of near-surface zooplankton, by varying the intensity and photoperiods of available visible light.

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